

Long Baseline Neutrino Physics (3)

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TASI 2006

Theoretical Advanced Study Institute
In Elementary Particle Physics
University of Colorado, June 4-30, 2006

4. The Value of Precision Neutrino Physics

precise neutrino parameters

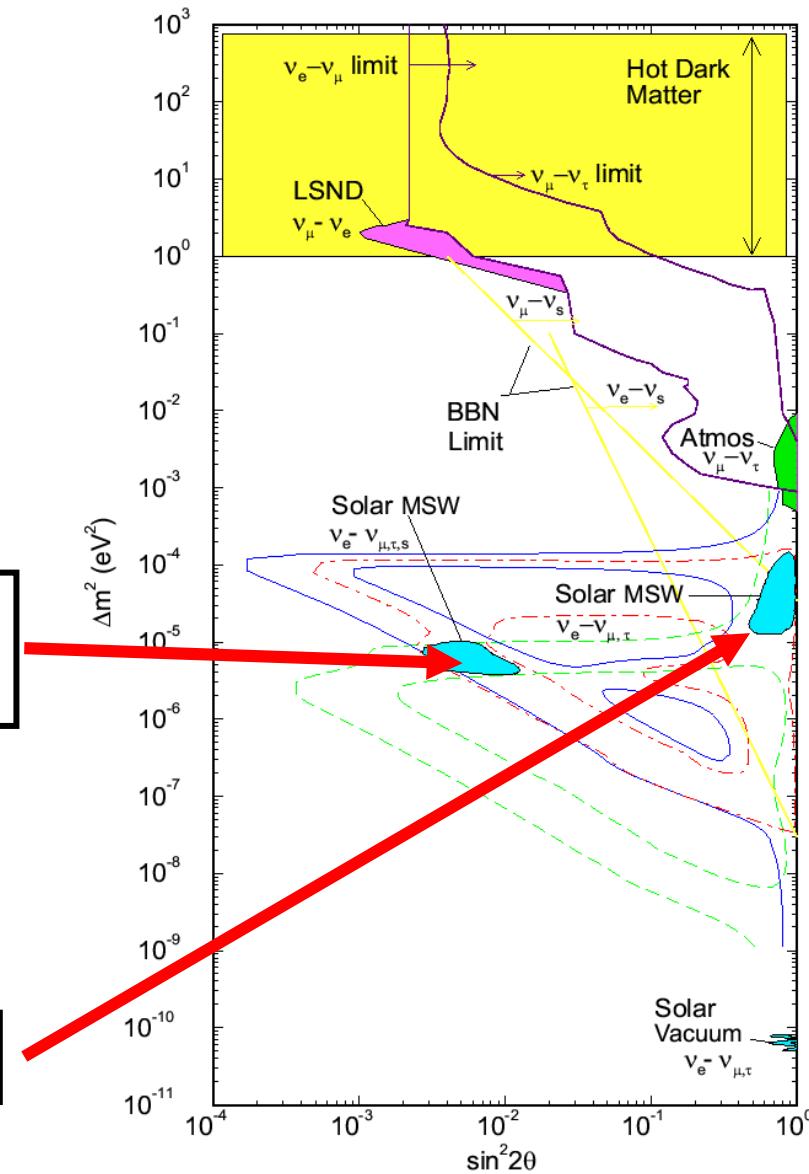
why is this interesting?

- unique flavour information
- very precise: no hadronic uncertainties
- apparent difference: quarks \leftrightarrow leptons
- tests models / ideas about flavour

History: Elimination of SMA

Was favoured by most theorists
↔ GUTs

preferred by nature



The Value of Precision for θ_{13}

- models of masses & mixings
- input: Known masses & mixings
→ distribution of θ_{13} „predictions“
- θ_{13} often close to experimental bounds
→ motivates new experiments
→ θ_{13} controls 3-flavour effects
like leptonic CP-violation

for example: $\sin^2 2\theta_{13} < 0.01 \rightarrow$

physics question: why is θ_{13} so small ?

- numerical coincidence
- symmetry

↔ precision!

Reference	$\sin \theta_{13}$	$\sin^2 2\theta_{13}$
<i>$SO(10)$</i>		
Goh, Mohapatra, Ng [40]	0.18	0.13
<i>Orbifold $SO(10)$</i>		
Anaka, Buchmüller, Covi [41]	0.1	0.04
<i>$SO(10) + flavor symmetry$</i>		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Mackawka [46]	0.22	0.18
Perez, Velasco, Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
<i>$SO(10) + texture$</i>		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4} .. 0.01$
<i>Flavor symmetries</i>		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
<i>Textures</i>		
Hondo, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4} .. 0.01$
Tbarra, Ross [61]	0.2	0.13
<i>3×2 see-saw</i>		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Flempton, Glashow, Veragida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy) (inverted hierarchy)	0.07 > 0.006	0.02 $> 1.6 \cdot 10^{-4}$
<i>Anarchy</i>		
de Gouvea, Murayama [66]	> 0.1	> 0.04
<i>Renormalization group enhancement</i>		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Further Implications of Precision

Precision allows to identify / exclude:

- special angles: $\theta_{13} = 0^\circ$, $\theta_{23} = 45^\circ$, ... \leftrightarrow discrete f. symmetries?
- special relations: $\theta_{12} + \theta_C = 45^\circ$? \leftrightarrow quark-lepton relation?
- quantum corrections \leftrightarrow renormalization group evolution

Provides also measurements or tests of:

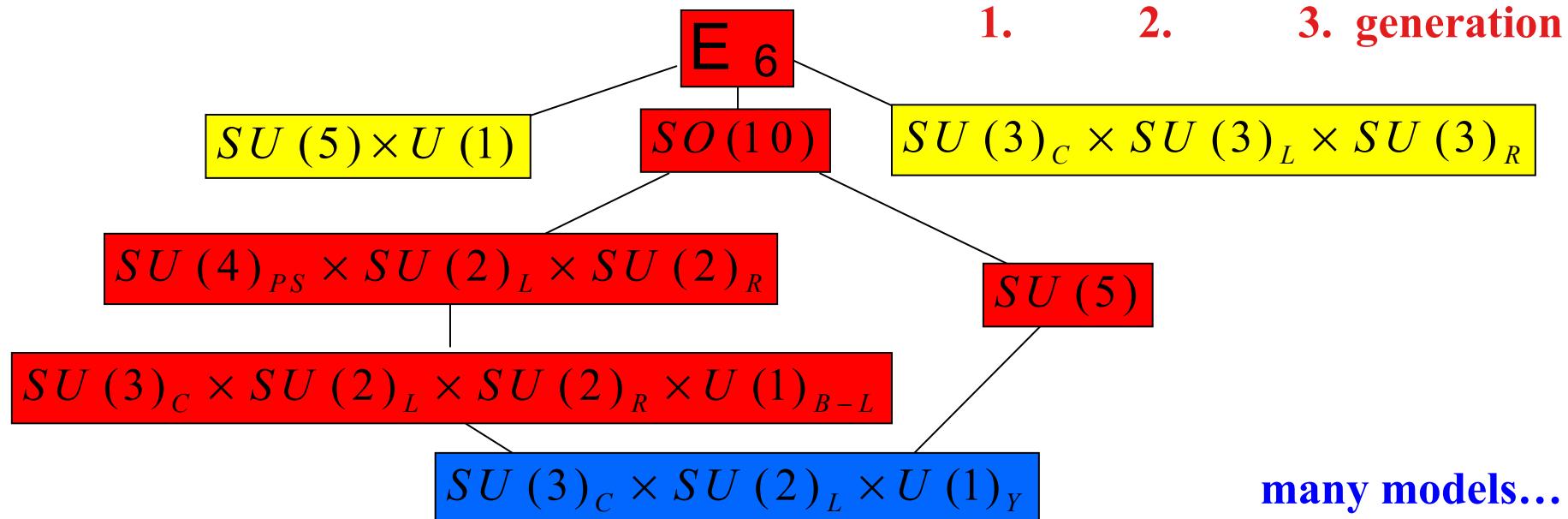
- MSW effect (coherent forward scattering and matter profiles)
- cross sections
- 3 neutrino unitarity \leftrightarrow sterile neutrinos with small mixings
- neutrino decay (admxiture...)
- decoherence
- NSI
- MVN, ...

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Requirements:
 gauge unification
 particle multiplets $\leftrightarrow v_R$
 proton decay

...



GUT Expectations and Requirements

Quarks and leptons sit in the same multiplets

- one set of Yukawa coupling for given GUT multiplet
- ~ tension: small quark mixings \leftrightarrow large leptonic mixings
- this was in fact the reason for the ‘prediction’ of
small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:

- sequential dominance
- type II see-saw
- Dirac screening
- ...

Single right-handed Dominance

$$m_D = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & a & b \\ \cdot & c & d \end{pmatrix} \quad M_R = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & x & 0 \\ \cdot & 0 & y \end{pmatrix}$$

$$\rightarrow m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \frac{a^2}{x} + \frac{b^2}{y} & \frac{ac}{x} + \frac{bd}{y} \\ \cdot & \frac{ac}{x} + \frac{bd}{y} & \frac{c^2}{x} + \frac{d^2}{y} \end{pmatrix}$$

If one right-handed neutrino dominates, e.g. $y \gg x$

- small sub-determinant $\sim m_2 \cdot m_3$
- $m_2 \ll m_3$ i.e. a natural hierarchy
- $\tan \theta_{23} \simeq a/c$ i.e. naturally large mixing

Sequential Dominance

$$m_D = \begin{pmatrix} a & b & c \\ d & e & f \\ g & e & h \end{pmatrix} \quad M_R = \begin{pmatrix} x & 0 & 0 \\ 0 & y & 0 \\ 0 & 0 & z \end{pmatrix}$$

$$m_\nu = -m_D \cdot M_R^{-1} \cdot m_D^T = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

sequential dominance: $z \gg y \gg x$

- small determinant $\sim m_1 \cdot m_2 \cdot m_3$
- $m_1 \ll m_2 \ll m_3$ natural
- naturally large mixings

S.F. King

Large Mixings and See-Saw Type II

see-saw type II

$$\mathbf{m}_v = \mathbf{M}_L - \mathbf{m}_D \mathbf{M}_R^{-1} \mathbf{m}_D^T$$

\mathbf{m}_D and \mathbf{M}_R may possess small mixings and hierarchy

However: \mathbf{M}_L can be numerically more important

Example: Break GUT \rightarrow $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow \mathbf{M}_L$ from LR

\rightarrow large mixings natural for almost degenerate case $m_1 \sim m_2 \sim m_3$

\rightarrow type I see-saw would only be a correction

type I – type II interference

$\rightarrow \mathbf{M}_L \simeq \mathbf{m}_D \mathbf{M}_R^{-1} \mathbf{m}_D^T$

\rightarrow many possibilities

Dirac Screening

Question: Do neutrino masses always depend on the Dirac Yukawa couplings? → no

ML, Schmidt, Smirnov

Assume: $v_L, v_R^C, S \rightarrow$

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu \langle \phi \rangle & 0 \\ Y_\nu^T \langle \phi \rangle & 0 & Y_N^T \langle \sigma \rangle \\ 0 & Y_N \langle \sigma \rangle & M_S \end{pmatrix}$$

→ double seesaw

$$m_\nu^0 = \left[\frac{\langle \phi \rangle}{\langle \sigma \rangle} \right]^2 Y_\nu (Y_N)^{-1} M_S (Y_N^T)^{-1} Y_\nu^T$$

fit fermions into GUT representations

→ relation between Yukawa couplings, e.g. E6

$$Y_\nu = c \cdot Y_N$$

Consequences of Dirac Screening

→ complete screening of
Dirac structure

$$m_\nu = c^2 \left[\frac{\langle \phi \rangle}{\langle \sigma \rangle} \right]^2 M_S$$

Outcome:

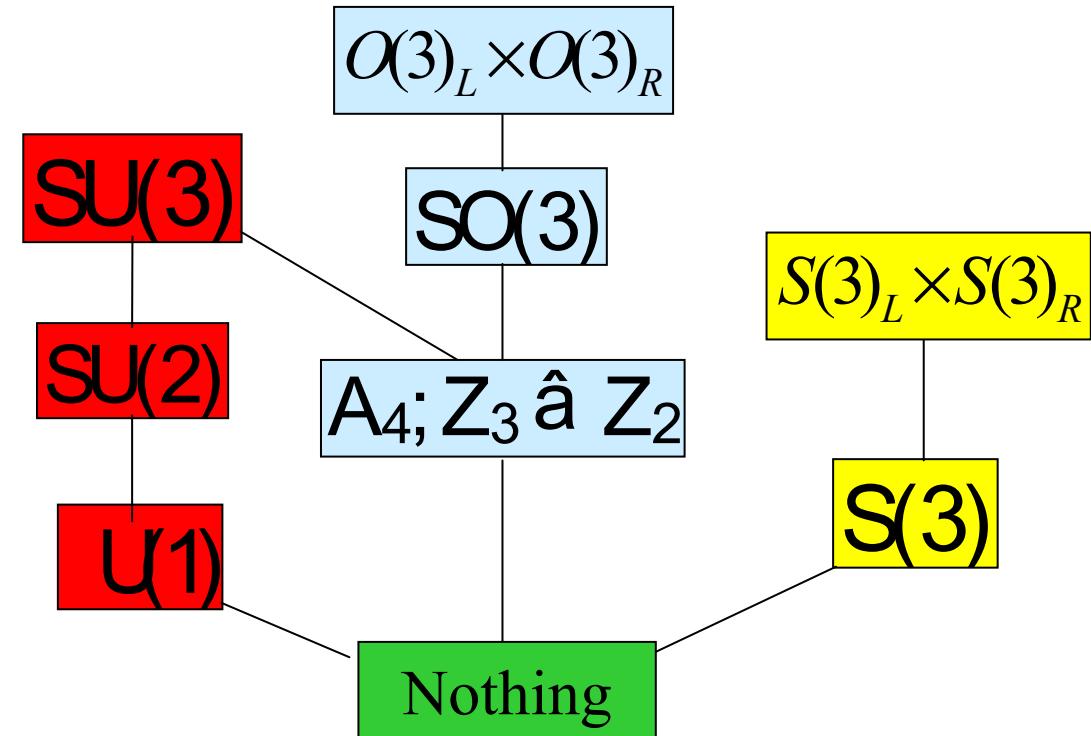
- Neutrino masses can emerge completely from Planck scale physics \leftrightarrow generically different
- Dirac Yukawa structure (small mixings) screened
- Hierarchical neutrino spectrum not required in see-saw
- Quark-lepton complimentarity possible ...
...with or without degenerate neutrino masses
- Double see-saw predicts for M_R to be below M_{GUT}
first see-saw → $M_R \sim \langle s \rangle / M_S \simeq 10^{-3} M_{GUT} \simeq 10^{13} \text{ GeV}$

Flavour Unification

- so far **no understanding of flavour, 3 generations**
- apparent regularities in quark and lepton parameters
→ flavour symmetries
→ not texture zeros

Quarks	u	c	t
	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
	~ 5	~ 1350	175000
d	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	~ 9	~ 175	~ 4500
Leptons	ν_1	ν_2	ν_3
	$0?$	$0?$	$0?$
1. 2. 3. generation	e	μ	τ
	0.511	105.66	1777.2

Examples:



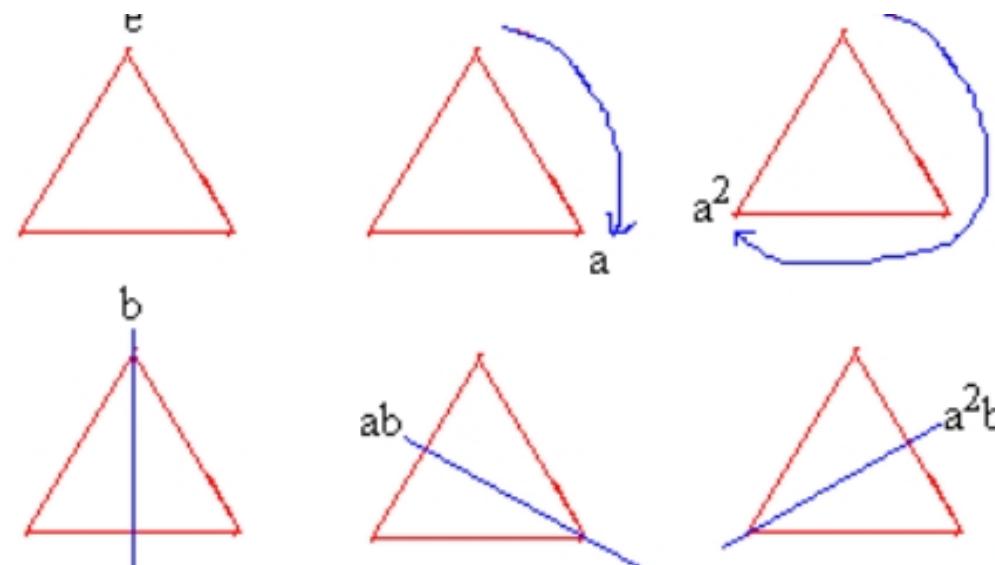
Discrete Flavour Symmetries

Discrete Flavour Symmetries \leftrightarrow flavour structure

Example: Dihedral groups D_n

$$\langle A, B | A^n = 1, B^2 = 1, (AB)^n = 1 \rangle$$

geometric
origin of D_3



Specific Example: D_5

Hagedorn, ML, Plentinger

$$\langle A, B | A^n = 1, B^2 = 1, (AB)^n = 1 \rangle .$$

complex generators

$$2_1: \quad A = \begin{pmatrix} e^{i\frac{2\pi}{5}} & 0 \\ 0 & e^{-i\frac{2\pi}{5}} \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$2_2: \quad A = \begin{pmatrix} e^{i\frac{4\pi}{5}} & 0 \\ 0 & e^{-i\frac{4\pi}{5}} \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

character table

classes	\mathcal{C}_1	\mathcal{C}_2	\mathcal{C}_3	\mathcal{C}_4
G	1	B	A	A^2
$h_{\mathcal{C}_i}$	1	5	2	2
$n_{\mathcal{C}_i}$	1	2	5	5
1_1	1	1	1	1
1_2	1	-1	1	1
2_1	2	0	$\frac{1}{2}(-1 + \sqrt{5})$	$\frac{1}{2}(-1 - \sqrt{5})$
2_2	2	0	$\frac{1}{2}(-1 - \sqrt{5})$	$\frac{1}{2}(-1 + \sqrt{5})$

Kronecker products

$$\begin{aligned} 1_1 \times 1_1 &= 1_1 \\ 1_2 \times 1_1 &= 1_2 \\ 2_1 \times 1_1 &= 2_1 \\ 2_2 \times 1_1 &= 2_2 \\ 1_2 \times 1_2 &= 1_1 \\ 2_1 \times 1_2 &= 2_1 \\ 2_2 \times 1_2 &= 2_2 \\ 2_1 \times 2_1 &= 1_1 + 1_2 + 2_2 \\ 2_2 \times 2_1 &= 2_1 + 2_2 \\ 2_2 \times 2_2 &= 1_1 + 1_2 + 2_1 \end{aligned}$$

Clebsch-Gordan Coefficients ...

D_5 Allowed Mass Terms

Task: search for mass terms which are for suitable Higgs singlets under D_5

Notation:

i_{th} generation fermions

$$L = \{L_1, L_2, L_3\}$$

Dirac mass terms:

$$\lambda_{ij} L_i^T (i\sigma_2) \phi L_j^c$$

Majorana mass terms:

$$\lambda_{ij} L_i^T \Xi \phi L_j$$

with

$$\Xi = \begin{pmatrix} \xi^0 & -\frac{\xi^+}{\sqrt{2}} \\ -\frac{\xi^+}{\sqrt{2}} & \xi^{++} \end{pmatrix}$$

Resulting D_5 Symmetry Texture

L	L^C	Mass Matrix
$(1_2, 1_1, 1_1)$	$(2_1, 1_1)$	$\begin{pmatrix} \kappa_1\psi_2^1 & -\kappa_1\psi_1^1 & \kappa_4\phi^2 \\ \kappa_2\psi_2^1 & \kappa_2\psi_1^1 & \kappa_5\phi^1 \\ \kappa_3\psi_2^1 & \kappa_3\psi_1^1 & \kappa_6\phi^1 \end{pmatrix}$

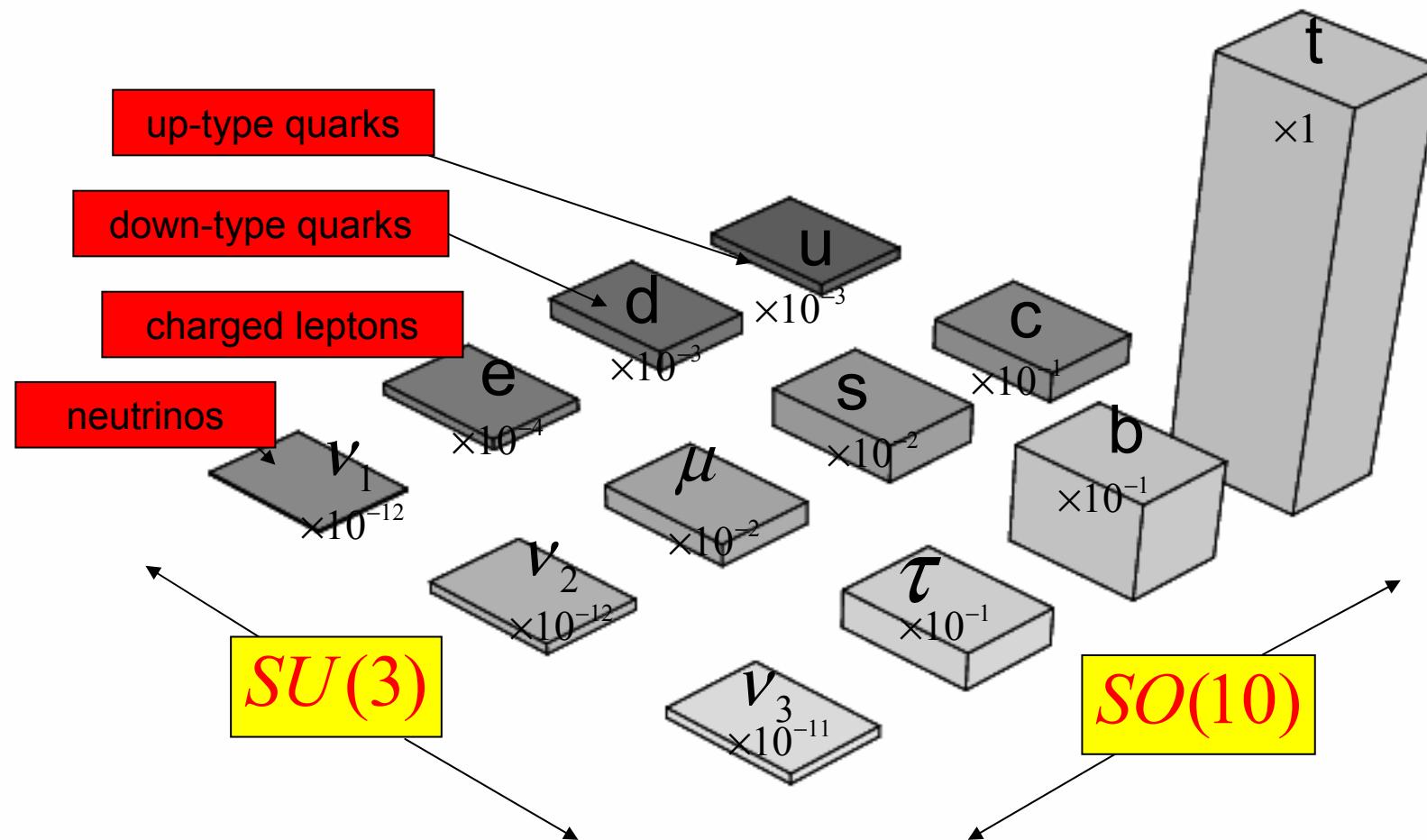
D5 singlet mass terms require the following quantum numbers for the scalars:

$$\begin{aligned} \phi_1 &\sim 1_1 , \\ \phi_2 &\sim 1_2 \text{ and} \\ \psi_1 &\sim 2_1 . \end{aligned}$$

→ Check if phenomenological successful predictions arise

GUT *and* Flavour Unification

Example: $SO(10) \times SU(3)$



GUT \otimes Flavour Unification

→ GUT group \otimes continuous, gauged flavour group

- for example $\text{SO}(10) \otimes \text{SU}(3)_{\text{flavour}}$
- Generations are 3_F
- SSB of $\text{SU}(3)_{\text{flavour}}$ between Λ_{GUT} and Λ_{Planck}
 - all flavour Goldstone Bosons eaten
 - discrete (ungauged) sub-group survives \leftrightarrow SSB potential
 - e.g. Z2, S3, D5, A4, ...
 - structures in flavour space

→ GUT \otimes flavour is rather restricted

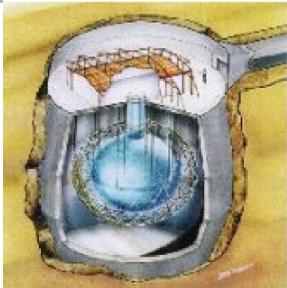
- small quark mixings
- large leptonic mixings
- from unified GUT \otimes flavour representations

GUT \otimes Flavour Challenges

- Difficulty grows with
 - size of flavour symmetry
 - size of the GUT group
- so far only a few viable models
e.g. SO(10) \otimes S4 Hagedorn, ML, Mohapatra
- limited number of possibilities
- phenomenological success non-trivial

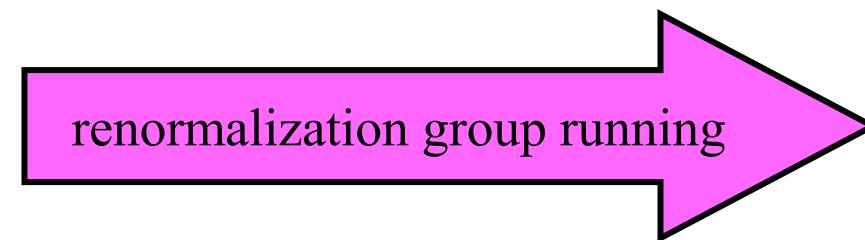
Aim: Distinguish models by future precision

Mass Models & Renormalization



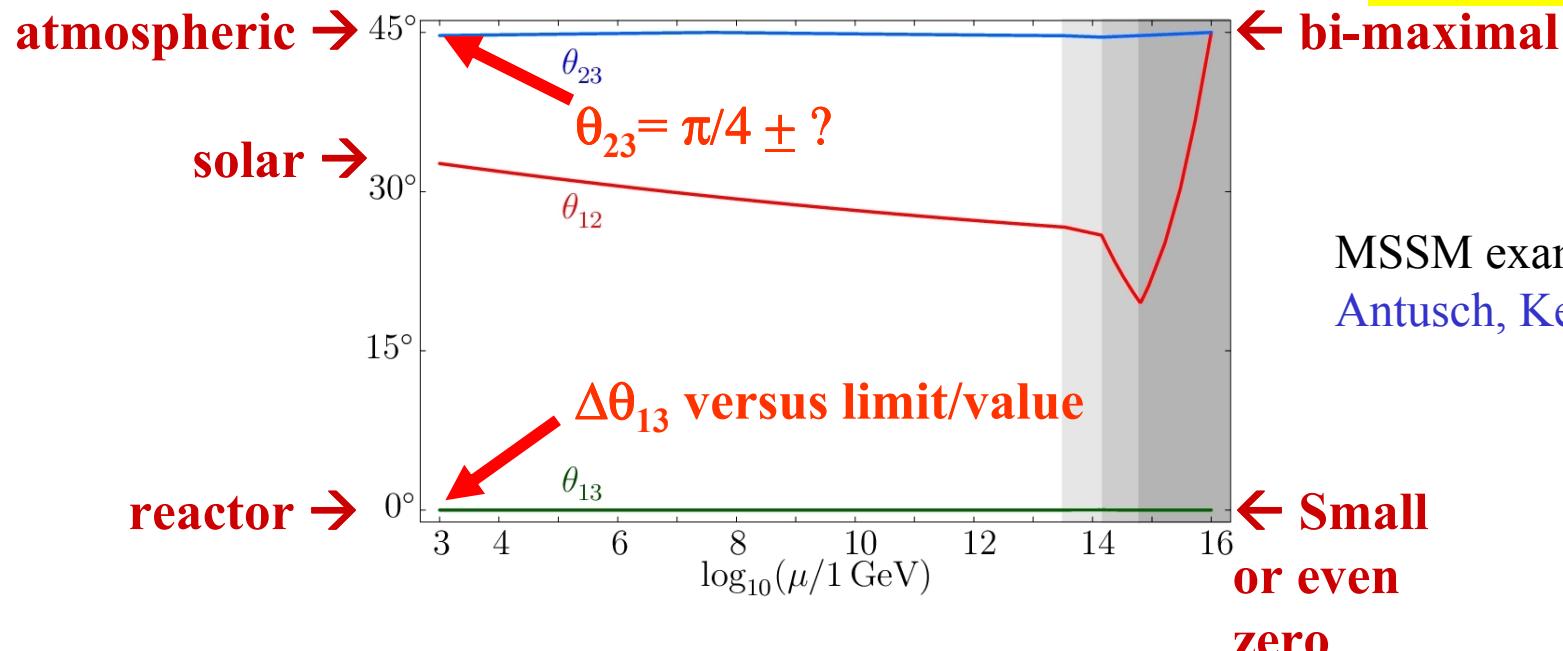
low energies:

- small masses
- large mixings



High energies:

- mass models
- flavour-symmetries
- GUT-models, ...



MSSM example:
Antusch, Kersten, **ML**, Ratz

d=5 Effective Neutrino Mass Operators

☞ Lowest dimensional effective neutrino mass operator in the SM:

$$\mathcal{L}_\kappa = \frac{1}{4} \kappa_{gf} \overline{\ell_L^C}^g \varepsilon^{cd} \phi_d \ell_L^f \varepsilon^{ba} \phi_a + \text{h.c.}$$

The diagram illustrates the coupling of the neutrino mass operator \mathcal{L}_κ to the left-handed lepton and scalar fields. The operator is shown in a red box. Three arrows point from three ovals below to the terms in the box: a red arrow labeled "Coupling" points to κ_{gf} ; a black arrow labeled $\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ points to $\overline{\ell_L^C}^g$ and ℓ_L^f ; and a green arrow labeled $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ points to ϕ_d and ϕ_a .

→ Majorana masses for the left-handed neutrinos

The diagram shows a square box labeled κ with four external lines: ϕ_a , ℓ_L^f , ℓ_L^g , and ϕ_d . An arrow labeled $\phi \rightarrow v + h$ and $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$ points to the right, where a neutrino ν_L and a scalar v are shown. Below this, another arrow labeled $\phi \rightarrow v + h$ and $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$ points to the right, leading to the field operator $\mathcal{L}_{\nu\nu} = \frac{1}{2} (m_\nu)_{gf} \overline{\nu_L^C}^g \nu_L^f + \text{h.c.}$. A blue oval at the bottom contains the equation $m_\nu = \frac{1}{2} \kappa \cdot v^2$.

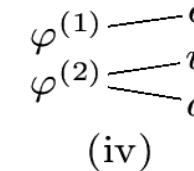
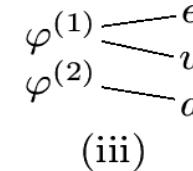
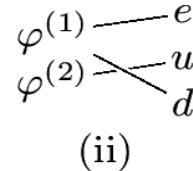
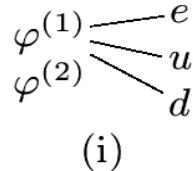
β_κ in the Standard Model

⌚ One-loop β -function

S. Antusch, M. Drees, J. Kersten, **ML**, M. Ratz

$$16\pi^2 \beta_\kappa = -\frac{3}{2}\kappa (Y_e^\dagger Y_e) - \frac{3}{2}(Y_e^\dagger Y_e)^T \kappa + \lambda\kappa - 3g_2^2\kappa + 2 \text{Tr}(Y_e^\dagger Y_e) \kappa + 6 \text{Tr}(Y_u^\dagger Y_u) \kappa + 6 \text{Tr}(Y_d^\dagger Y_d) \kappa$$

β_κ in 2Higgs Models



$$\mathcal{L}_\kappa^{(ii)} = \frac{1}{4} \kappa_{gf}^{(ii)} \overline{\ell_L}^C_c \varepsilon^{cd} \varphi^{(i)}_d \ell_L^f b \varepsilon^{ba} \varphi^{(i)}_a + \text{h.c.} \quad (i = 1, 2)$$



non-diagonal

	(i)	(ii)	(iii)	(iv)
$z_u^{(1)}$	1	0	1	0
$z_u^{(2)}$	0	1	0	1
$z_d^{(1)}$	1	1	0	0
$z_d^{(2)}$	0	0	1	1

$$16\pi^2 \beta_{\kappa^{(ii)}} = \left(\frac{1}{2} - 2\delta_{i1}\right) [\kappa^{(ii)} (\overline{Y_e^\dagger} Y_e) + (\overline{Y_e^\dagger} Y_e)^T \kappa^{(ii)}] + \left[\delta_{i1} 2 \operatorname{Tr}(Y_e^\dagger Y_e) + z_u^{(i)} 6 \operatorname{Tr}(Y_u^\dagger Y_u) + z_d^{(i)} 6 \operatorname{Tr}(Y_d^\dagger Y_d)\right] \kappa^{(ii)} + \lambda_i \kappa^{(ii)} + \delta_{i1} \lambda_5^* \kappa^{(22)} + \delta_{i2} \lambda_5 \kappa^{(11)} - 3g_2^2 \kappa^{(ii)}$$

mixing

Antusch, Drees, Kersten, **ML**, Ratz, Phys. Lett. B525 (2002) 130

β_κ in the MSSM

☒ 1-loop

P.H. Chankowski, Z. Pluciennik (1993)
 K.S. Babu, C.N. Leung, J. Pantaleone (1993)

$$(4\pi)^2 \beta_\kappa^{(1)} = \left[-\frac{6}{5} g_1^2 - 6 g_2^2 + 6 \text{Tr}(Y_u^\dagger Y_u) \right] \kappa + (Y_e^\dagger Y_e)^T \kappa + \kappa (Y_e^\dagger Y_e)$$

☒ 2-loop

S. Antusch, M. Ratz

$$\begin{aligned} (4\pi)^4 \beta_\kappa^{(2)} = & \left[-6 \text{Tr}(Y_u^\dagger Y_d Y_d^\dagger Y_u) - 18 \text{Tr}(Y_u^\dagger Y_u Y_u^\dagger Y_u) + \frac{8}{5} g_1^2 \text{Tr}(Y_u^\dagger Y_u) \right. \\ & + 32 g_3^2 \text{Tr}(Y_u^\dagger Y_u) + \frac{207}{25} g_1^4 + \frac{18}{5} g_1^2 g_2^2 + 15 g_2^4 \Big] \kappa \\ & - \left[2 (Y_e^\dagger Y_e Y_e^\dagger Y_e)^T - \left(\frac{6}{5} g_1^2 - \text{Tr}(Y_e Y_e^\dagger) - 3 \text{Tr}(Y_d Y_d^\dagger) \right) (Y_e^\dagger Y_e)^T \right] \kappa \\ & - \kappa \left[2 Y_e^\dagger Y_e Y_e^\dagger Y_e - \left(\frac{6}{5} g_1^2 - \text{Tr}(Y_e Y_e^\dagger) - 3 \text{Tr}(Y_d Y_d^\dagger) \right) Y_e^\dagger Y_e \right] \end{aligned}$$

Analytic Formulae

J. Casas, J. Espinosa, A. Ibarra, I. Navarro

P. Chankowski, W. Krolikowski, S. Pokorski

S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

☛ Expand in θ_{13} (and neglect $y_\mu, y_e \ll y_\tau$)

The diagram illustrates the renormalization group flow. Two ovals at the top represent the 'Renormalization scale' and 'MSSM $C = 1$, SM $C = -3/2$ '. Arrows from these ovals point to the corresponding terms in the evolution equations below.

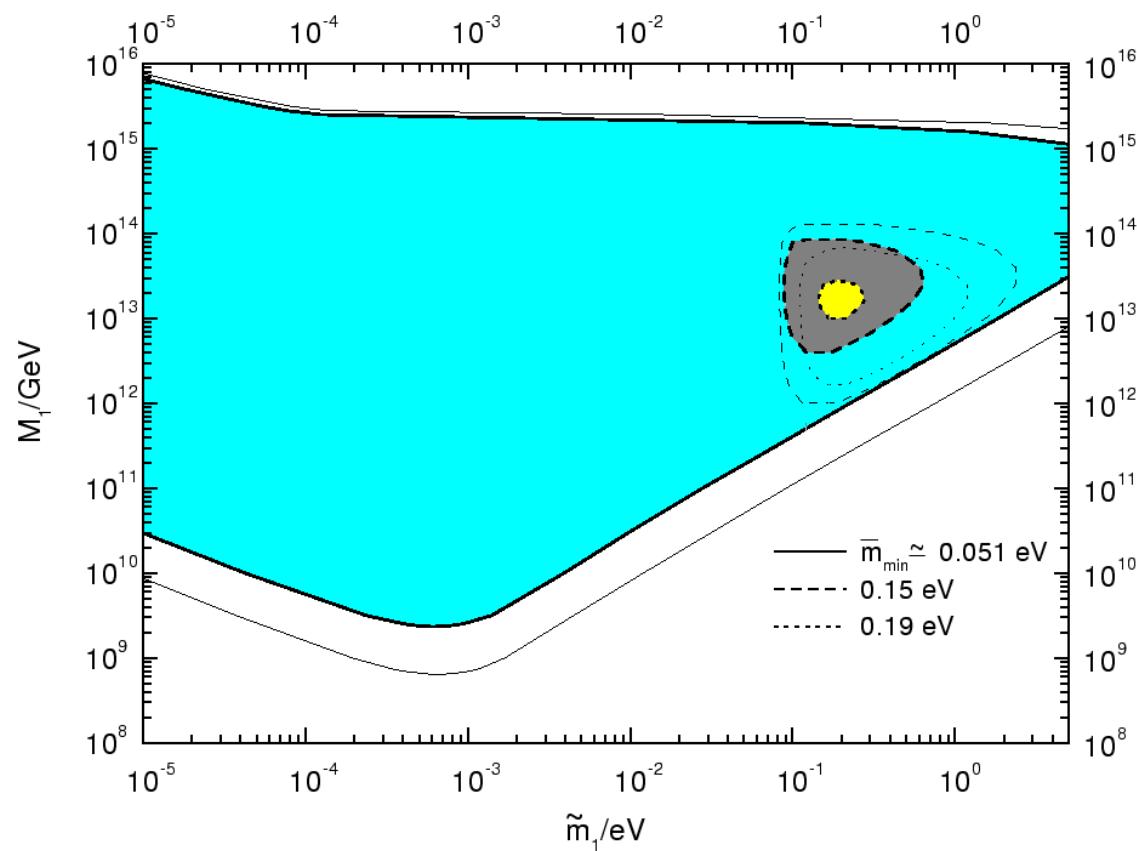
$$\begin{aligned} \mu \frac{d}{d\mu} \theta_{12} &= -\frac{C y_\tau^2}{32\pi^2} \sin 2\theta_{12} \sin^2 \theta_{23} \frac{|m_1 e^{i\varphi_1} + m_2 e^{i\varphi_2}|^2}{\Delta m_{\text{sol}}^2} + \mathcal{O}(\theta_{13}) \\ \mu \frac{d}{d\mu} \theta_{13} &= \frac{C y_\tau^2}{32\pi^2} \sin 2\theta_{12} \sin 2\theta_{23} \frac{m_3}{\Delta m_{\text{atm}}^2 (1 + \zeta)} \times \\ &\quad \times [m_1 \cos(\varphi_1 - \delta) - (1 + \zeta) m_2 \cos(\varphi_2 - \delta) - \zeta m_3 \cos \delta] + \mathcal{O}(\theta_{13}) \\ \mu \frac{d}{d\mu} \theta_{23} &= -\frac{C y_\tau^2}{32\pi^2} \sin 2\theta_{23} \frac{1}{\Delta m_{\text{atm}}^2} \times \\ &\quad \times \left[\cos^2 \theta_{12} |m_2 e^{i\varphi_2} + m_3|^2 + \sin^2 \theta_{12} \frac{|m_1 e^{i\varphi_1} + m_3|^2}{1 + \zeta} \right] + \mathcal{O}(\theta_{13}) \end{aligned}$$

$\zeta = \frac{\Delta m_{\text{sol}}^2}{\Delta m_{\text{atm}}^2}$

Implications for Leptogenesis

☞ Mass window for leptogenesis

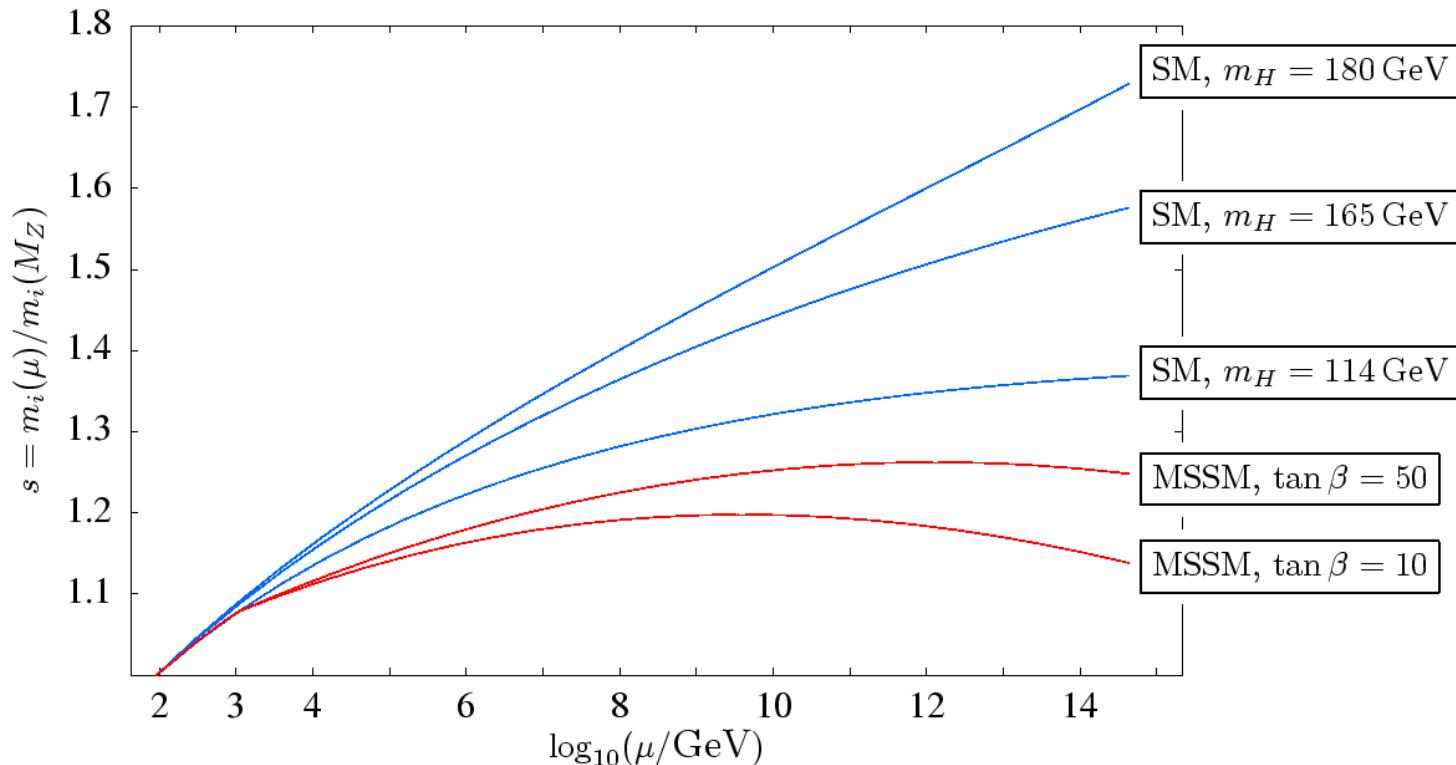
W. Buchmüller, P. di Bari, M. Plümacher



Implications for Leptogenesis

☞ RG scaling of masses

S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

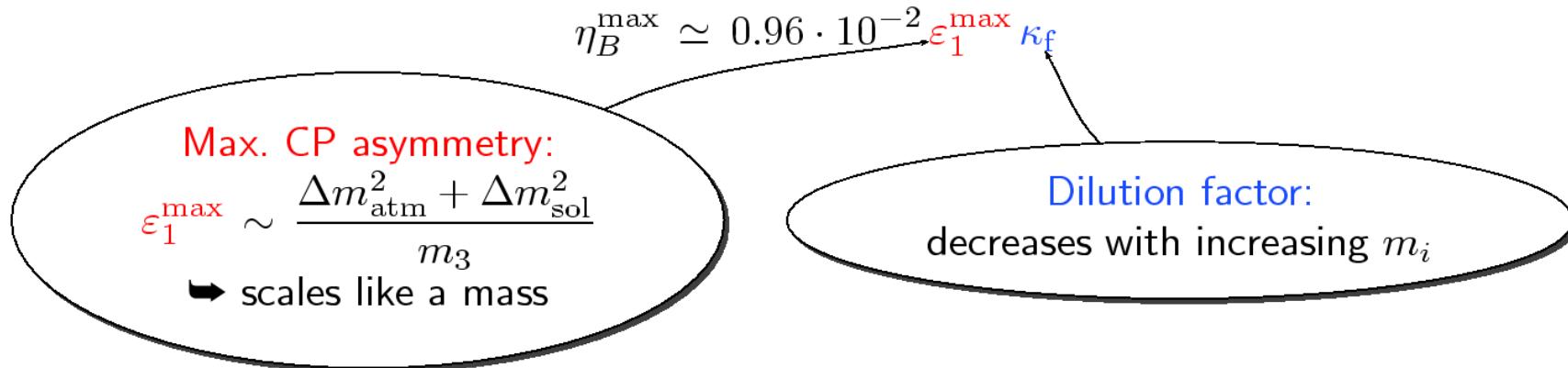


☞ Describes RG evolution except for MSSM with large $\tan \beta$ and degenerate masses

Implications for Leptogenesis

- ☞ Maximal baryon asymmetry

W. Buchmüller, P. di Bari, M. Plümacher



- ☞ Numerically: Dilution factor wins at the edge of the 'mass window'

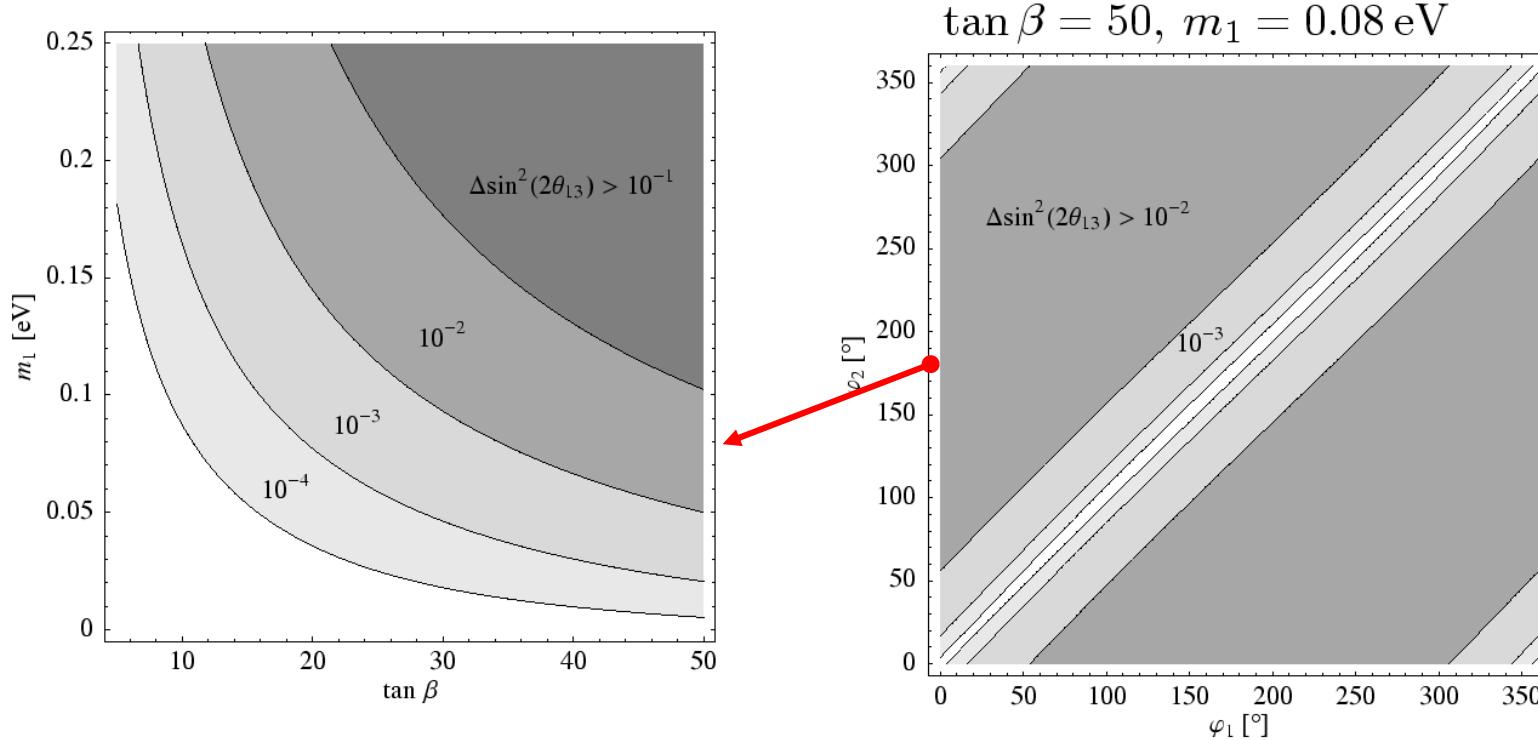
→ 'Mass window' will become smaller

S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

- ☞ Exception: MSSM with large $\tan \beta$ and degenerate masses

RG Evolution of θ_{13}

- Violation of a high-energy symmetry by RG effects: Assume $\theta_{13} = 0$ @ $M_1 = 10^{12}$ GeV

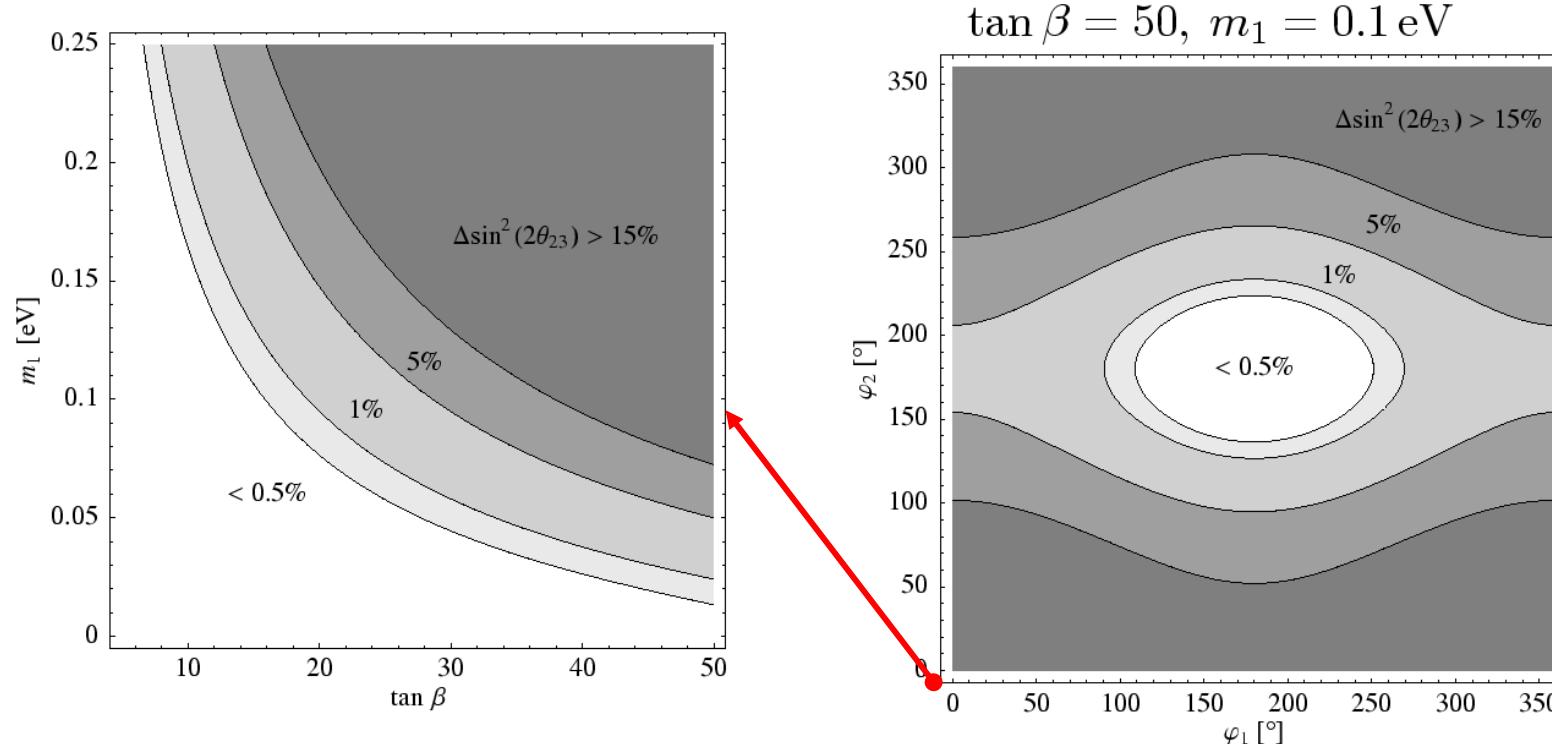


- RG change may be measurable

S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](https://arxiv.org/abs/hep-ph/0305273)

RG Evolution of θ_{23}

☛ Violation of a high-energy symmetry by RG effects: Assume $\theta_{23} = 45^\circ$ @ $M_1 = 10^{12}$ GeV



► RG change may be measurable

S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

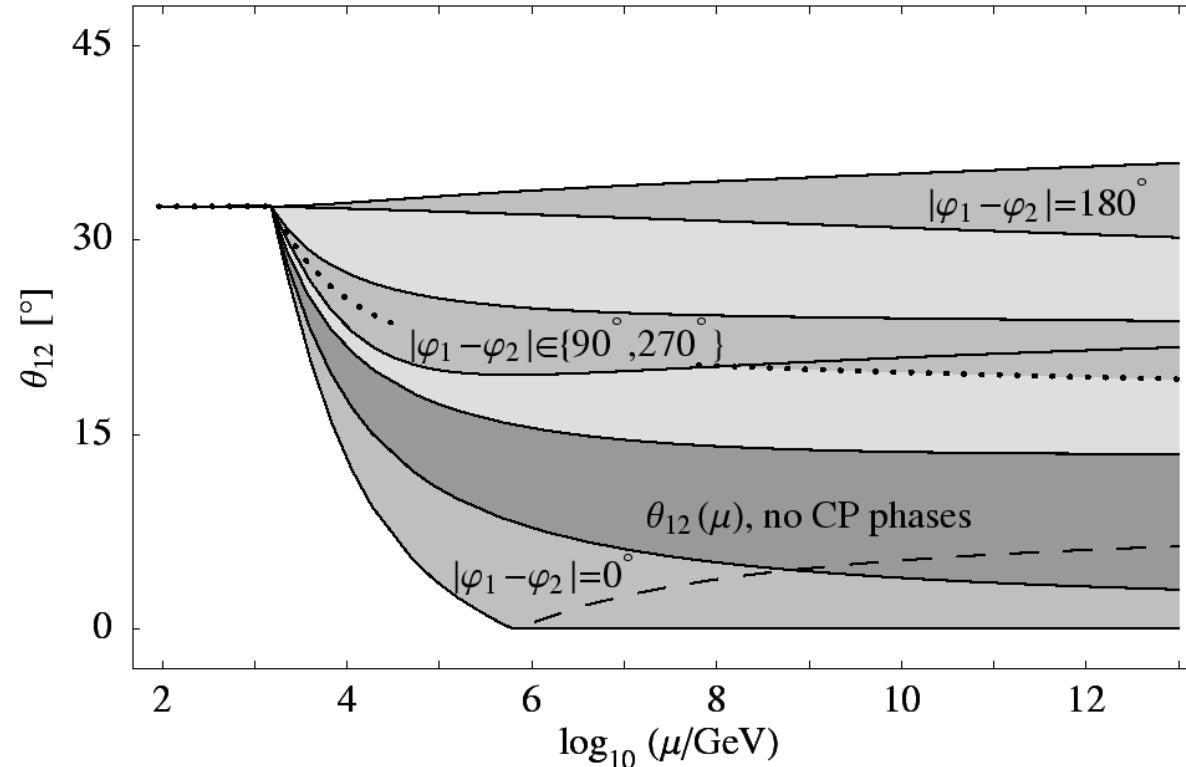
RG Evolution of θ_{12}

$$\mu \frac{d}{d\mu} \theta_{12} = -\frac{y_\tau^2}{32\pi^2} \sin 2\theta_{12} \sin^2 \theta_{23} \frac{|m_1 e^{i\varphi_1} + m_2 e^{i\varphi_2}|^2}{\Delta m_{\text{sol}}^2} + \mathcal{O}(\theta_{13})$$

MSSM
 $\tan \beta=50$
 $m_1=0.1\text{eV}$

dark:
 $\theta_{13} \in [0^\circ, 9^\circ]$
CP phases=0

medium:
→ phases
 $\theta_{13} \in [0^\circ, 9^\circ]$
 $\delta=0, \pi/2, \pi, 3\pi/2$



light: remaining CP phases

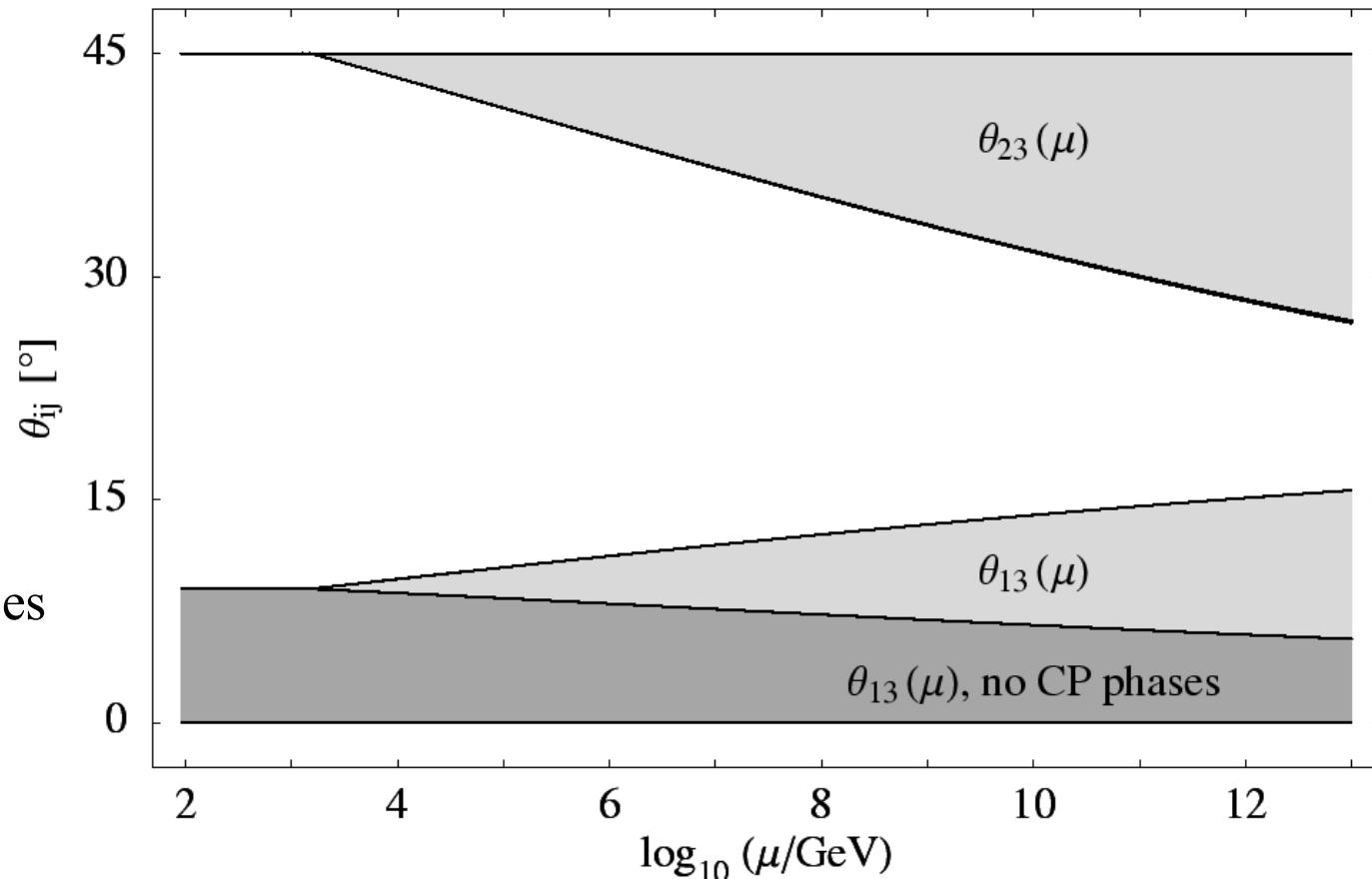
S. Antusch, J. Kersten, **ML**, M. Ratz hep-ph/0305273

Evolution of θ_{13} and θ_{23}

MSSM
 $\tan \beta = 50$
 $m_1 = 0.1\text{eV}$

dark:
 $\theta_{13} \in [0^\circ, 9^\circ]$
CP phases=0

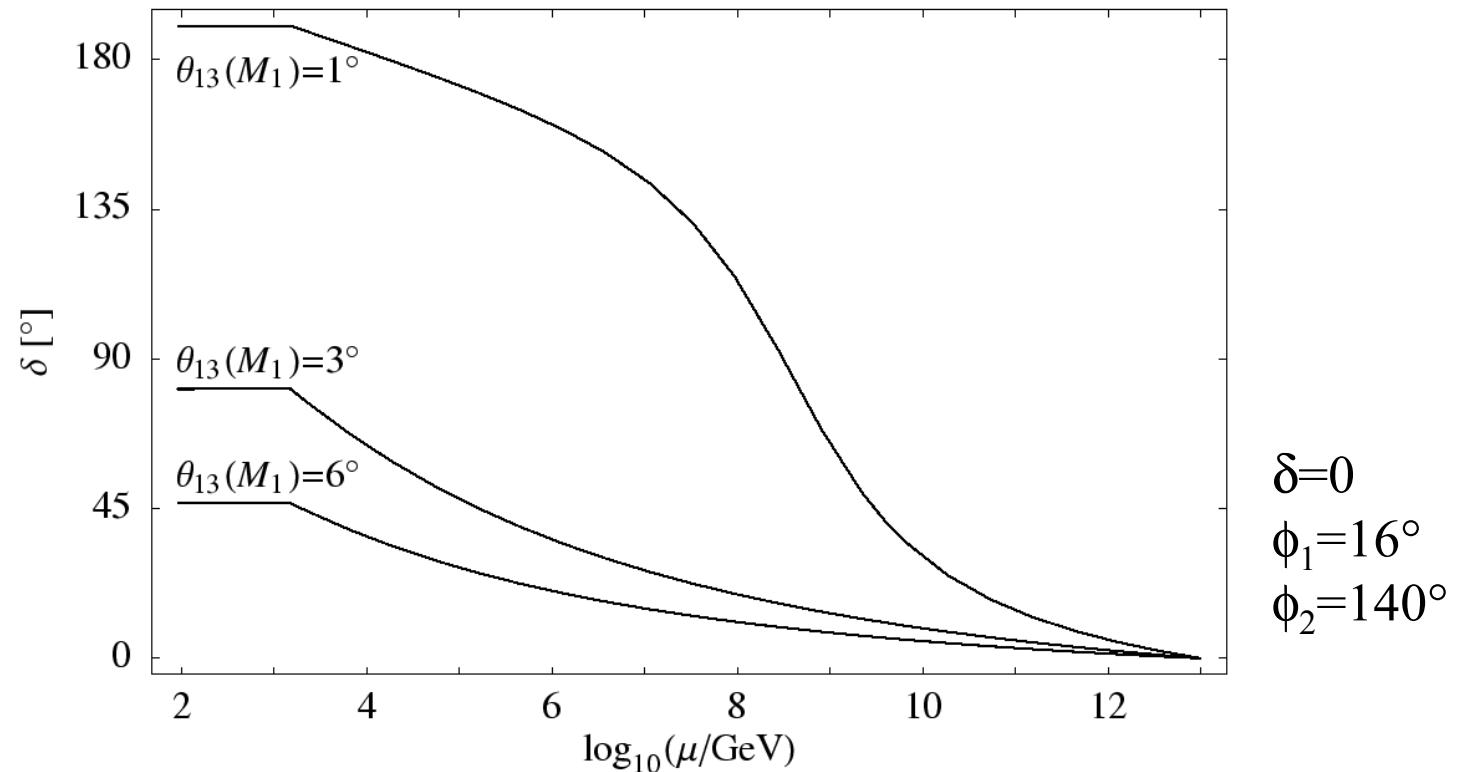
light:
arbitrary CP phases



S. Antusch, J. Kersten, **ML**, M. Ratz

Radiative Generation of Dirac Phase δ

☞ Constellation: $\tan \beta = 30$, $m_1 = 0.17 \text{ eV}$, $\varphi_1 = 16^\circ$ and $\varphi_2 = 140^\circ$ @ $M_1 = 10^{13} \text{ GeV}$



J. Casas, J. Espinosa, A. Ibarra, I. Navarro

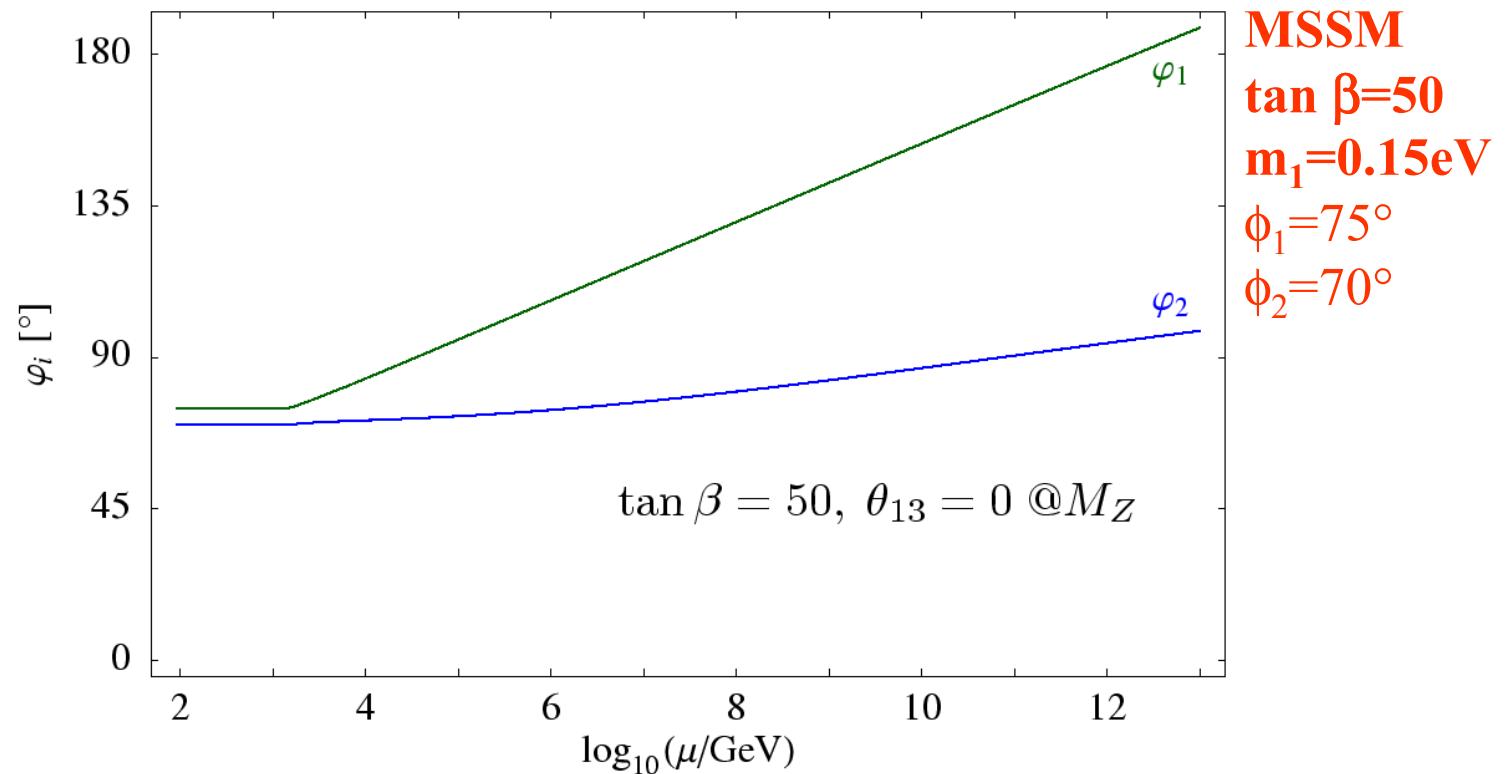
S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](https://arxiv.org/abs/hep-ph/0305273)

Evolution of Majorana Phases

Phase difference tends to decrease

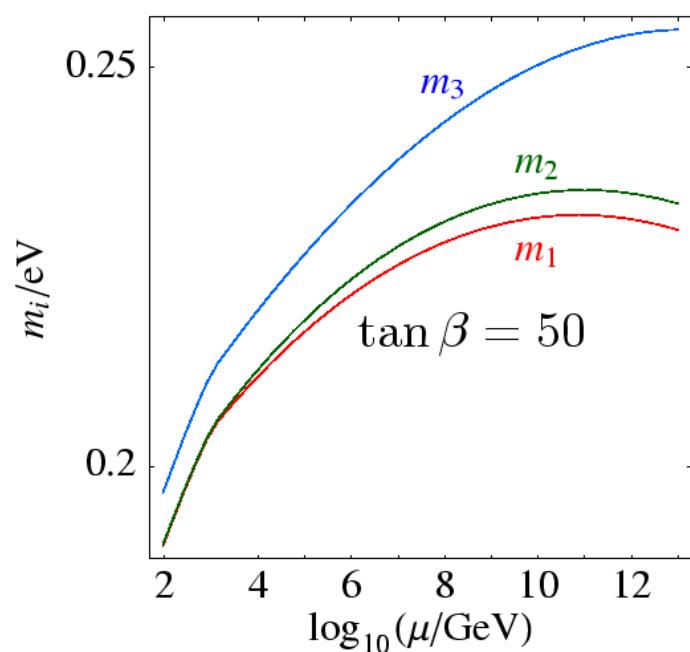
S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

$$\dot{\varphi}_1 - \dot{\varphi}_2 = \frac{y_\tau^2}{4\pi^2} \frac{m_1 m_2}{\Delta m_{\text{sol}}^2} \cos 2\theta_{12} \sin^2 \theta_{23} \sin(\varphi_1 - \varphi_2) + \mathcal{O}(\theta_{13})$$

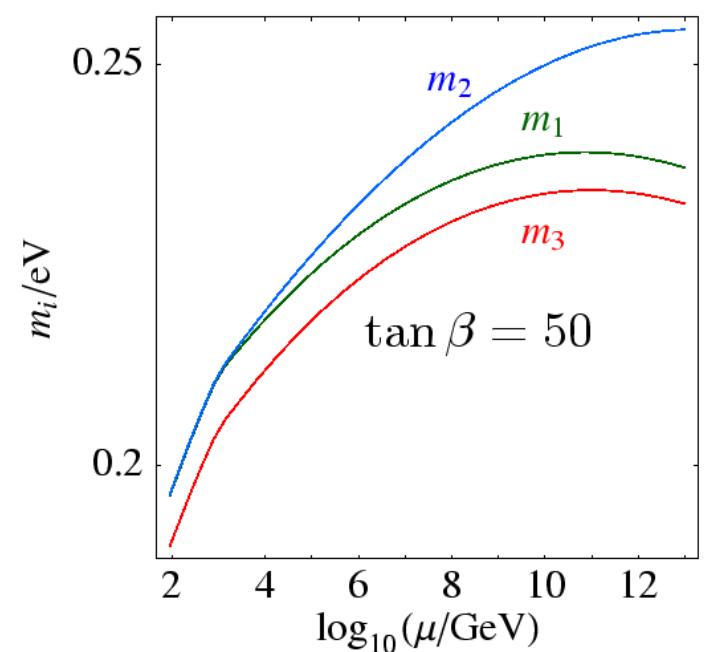


Extreme Examples

normal hierarchy, $m_{\min} = 0.19\text{eV}$



inverted hierarchy , $m_{\min} = 0.19\text{eV}$

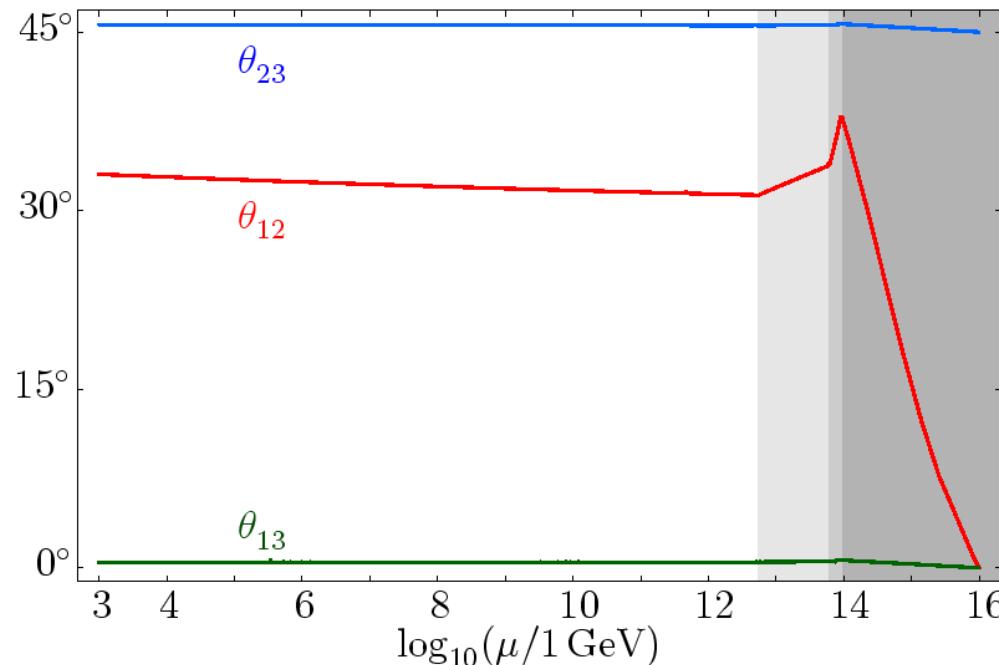


S. Antusch, J. Kersten, **ML**, M. Ratz [hep-ph/0305273](#)

RG Running above lowest Threshold

Non-degenerate heavy Majorana thresholds:

- above all thresholds: running Y, M_R
- successively integrate out heavy Majorana fields



→ RG evolution in general **stronger**

S. King, M. Singh

S. Antusch, J. Kersten, **ML**, M. Ratz

S. Antusch, M. Ratz

RG Running & Flavour Textures

- neutrino masses & mixings \leftrightarrow flavour textures at high energies
- only certain texture-zero mass matrices are allowed

P.H. Frampton, S.L. Glashow, D. Marfatia
W.-I. Guo, Z.-z. Xing

- RG running \rightarrow previously forbidden textures \rightarrow

$$\begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}, \begin{pmatrix} \times & 0 & \times \\ 0 & \times & 0 \\ \times & 0 & \times \end{pmatrix}, \begin{pmatrix} \times & \times & 0 \\ \times & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

\rightarrow class F
becomes allowed

$$\begin{pmatrix} 0 & \times & \times \\ \times & 0 & \times \\ \times & \times & \times \end{pmatrix}, \begin{pmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & 0 \end{pmatrix}, \begin{pmatrix} 0 & \times & \times \\ \times & \times & 0 \\ \times & 0 & \times \end{pmatrix}$$

\rightarrow class E
remains forbidden

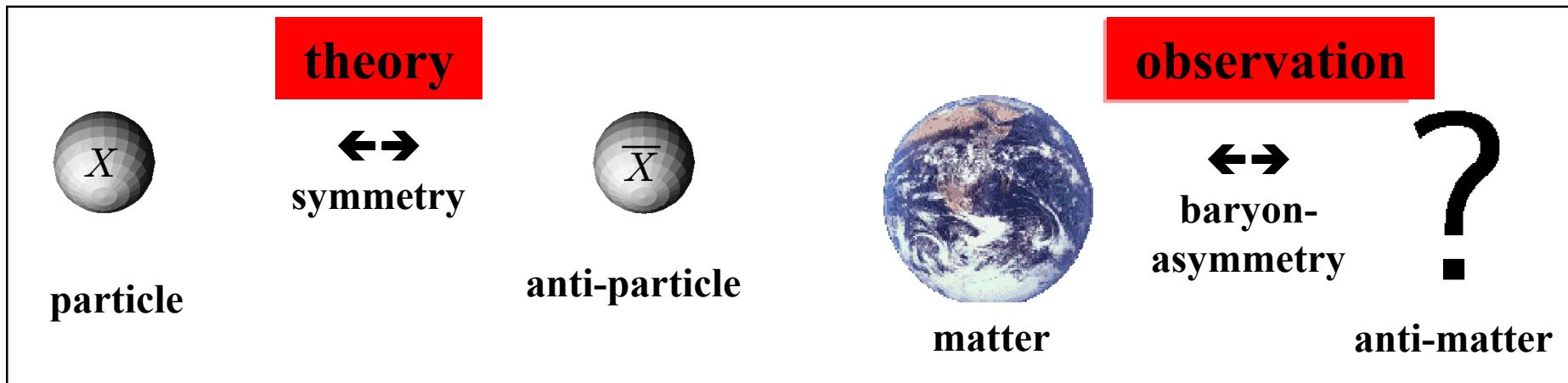
- even some 3 zero textures become allowed! ...other textures

C. Hagedorn, **ML**, J. Kersten, hep-ph/0406103

RG-Conclusions

- RG effects **connect measurements and high energy models**
- are important – especially for non-hierarchical masses
- simple analytic expressions (including CP phases)
- important effects from integrating out M_R thresholds
- RG effects have interesting phenomenological consequences:
 - leptogenesis → smaller mass window
 - textures vs. data → more solutions
 - evolution of θ_{13} and θ_{23} ↔ future precision
 - interesting evolution effects for CP phases
 - ...
 - neutrino-less double β-decay
 - WMAP
 - ...

Baryon Asymmetry



measured baryon asymmetry: $\eta = \frac{n_B}{n_\gamma} = 4(3) \cdot 10^{-10} \dots 7(10) \cdot 10^{-10}$

Necessary: Sakharov conditions:

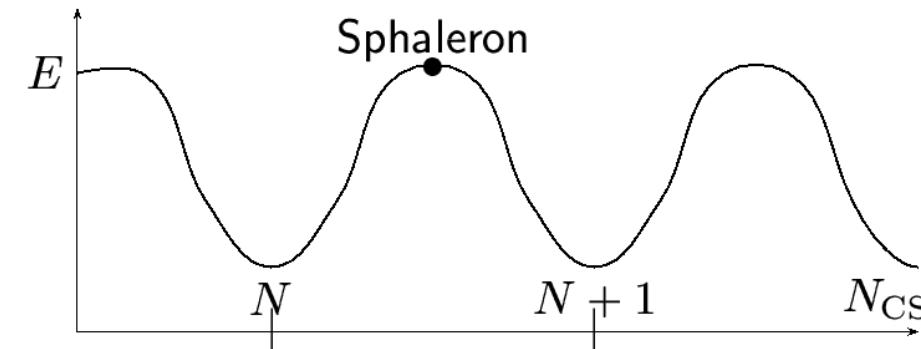
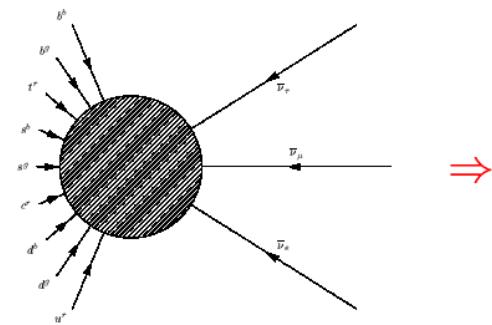
- B-violating processes
- C- and CP-violation
- departure from thermal equilibrium

Realization of the Sakharov Conditions

- **Baryogenesis \Rightarrow Sakharov conditions:**

1. **C & CP violation** \leftrightarrow complex couplings in \mathcal{L}
2. **Departure from thermal equilibrium** $\leftrightarrow \Gamma < H$
3. **B violation** \leftrightarrow B+L violating Sphalerons

- **Sphaleron Processes:** \leftrightarrow topology of electro-weak vacuum

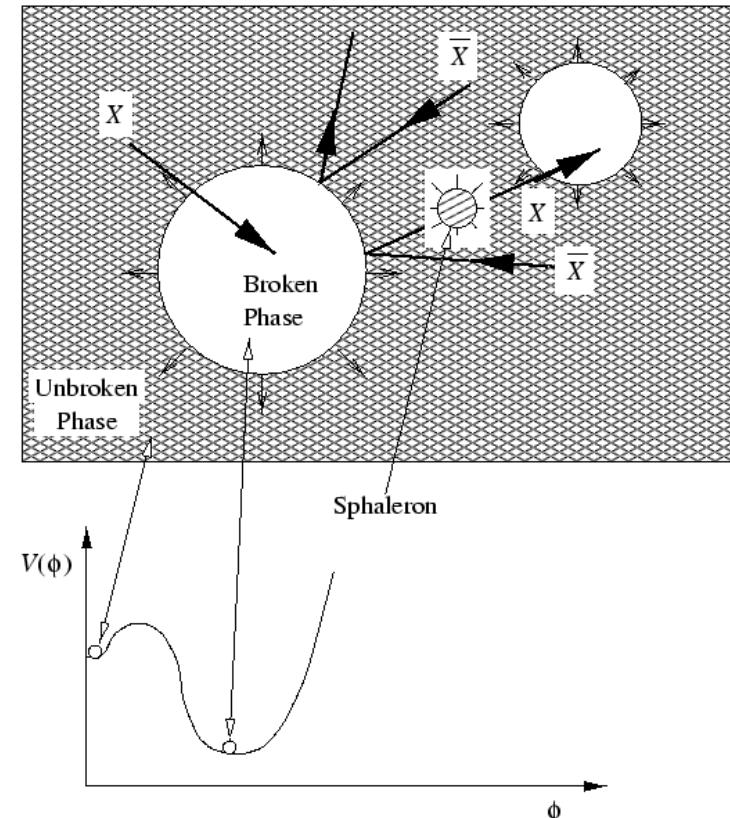


- Sphaleron processes are in equilibrium for $T \gtrsim T_{EW}$
- Sphaleron processes stop for $T < T_{EW}$
- Provide \cancel{B}
- Change $(B+L)$, but not $(B-L)$
- Only lefthanded particles are affected \leftrightarrow lepton number assignment & equilibration

Electroweak Baryogenesis

- SM fulfills Sakharov conditions
- CP violation is tiny
- requires a **1st order phase transition:**
 - growing bubbles of the broken vacuum
 - asymmetric scattering of particles and anti-particles

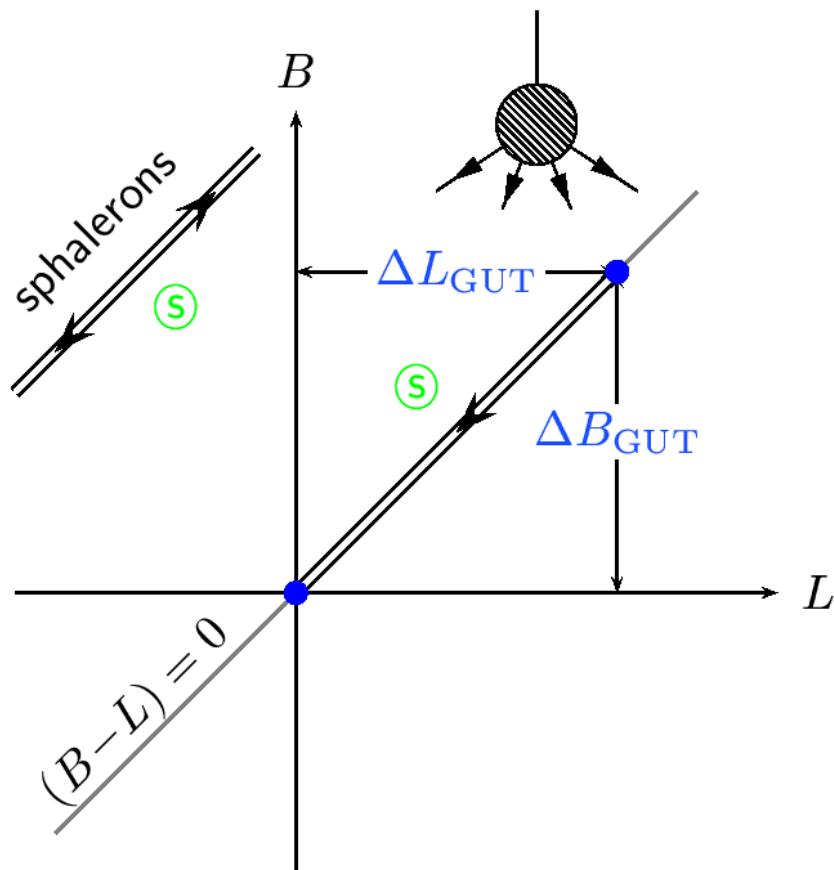
However: Phase transition is most likely a ``cross-over“ or at best 2nd order



- Electroweak Baryogenesis **does not work within the Standard Model**
- 1st order phase transition \Rightarrow one tiny λ \Rightarrow **tendency to predict light Higgses**
 \Rightarrow almost excluded in extensions like 2HDM, MSSM, ...

GUT Baryogenesis and the Wash-Out

Kuzmin, Rubakov & Shaposhnikov

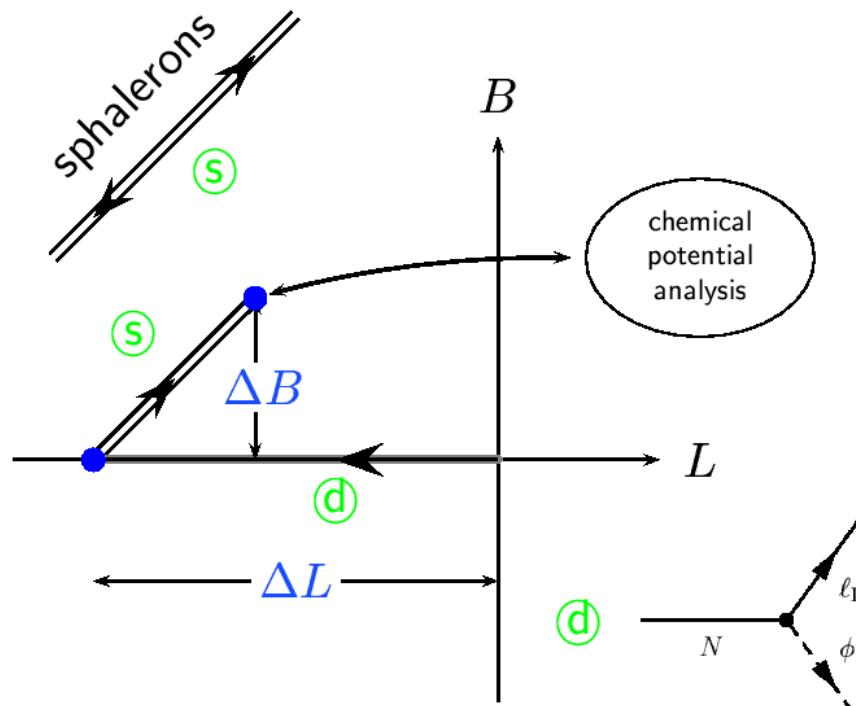


- GUT decays produce an initial B asymmetry
- typically B-L conserved
- sphalerons change $B+L \rightarrow B=L=0$
- ``wash-out`` of any initial B as long as B-L is conserved

Leptogenesis

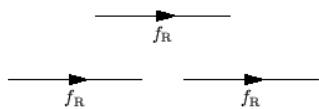
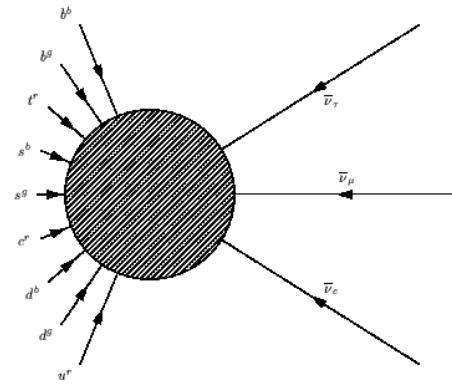
Fukugita & Yanagida, Luty, Buchmüller et al

- Righthanded Majorana neutrinos decays \textcircled{d} produce ΔL ($\leftrightarrow \bar{L}$)
- Sphalerons \textcircled{S} convert ΔL partially into ΔB

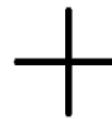
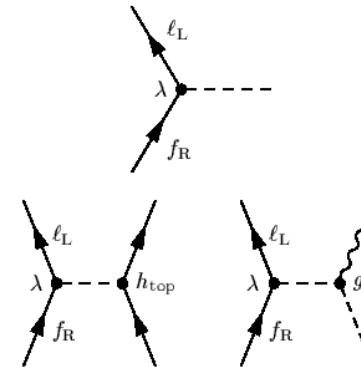


- ⇒ Sphalerons convert a L asymmetry into a B asymmetry
⇒ upper bound on $m_\nu < \mathcal{O}(0.1 \text{ eV})$ Buchmuller, Plumacher, Int.J.Mod.Phys.A15 (2000)5047

Wash-out and Equilibration



Only lefthanded particles
are affected.



$$\mathcal{L} = \lambda \bar{f}_R (\varphi \ell_L) + \text{h.c.}$$

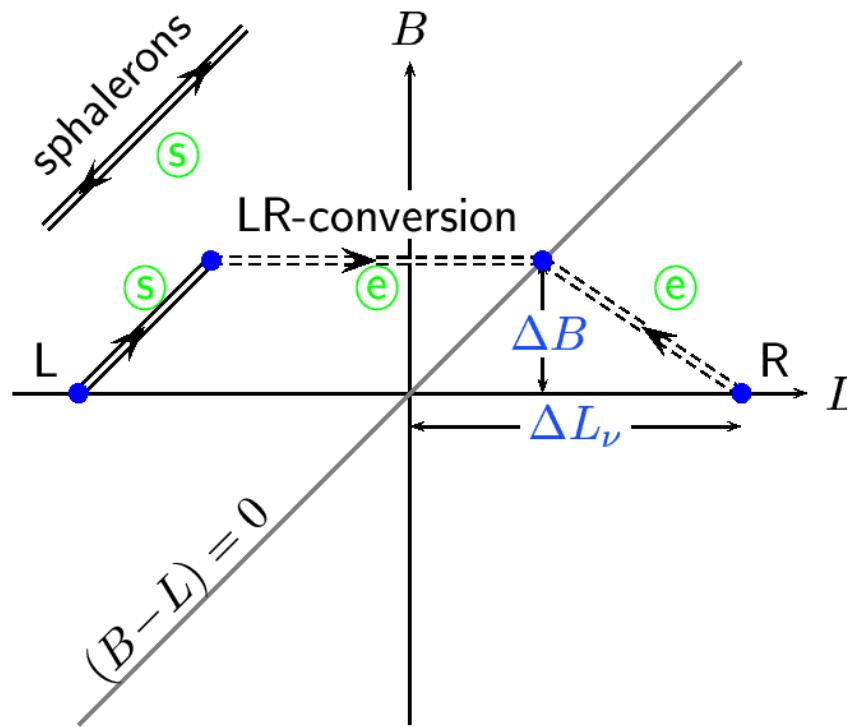
LR-conversion \leftrightarrow
Higgs-Yukawa-couplings.

- Equilibration very fast for sizable Yukawa couplings \Rightarrow ignore
- Small Yukawa couplings \Rightarrow treat $SU(2)$ singlets separately

Neutrinogenesis

Dick, Lindner, Ratz, Wright, Phys. Rev. Lett. 84 (2000) 4039

- Small Yukawa couplings \Rightarrow LR-conversion too slow
- Equilibration occurs after sphalerons switch off

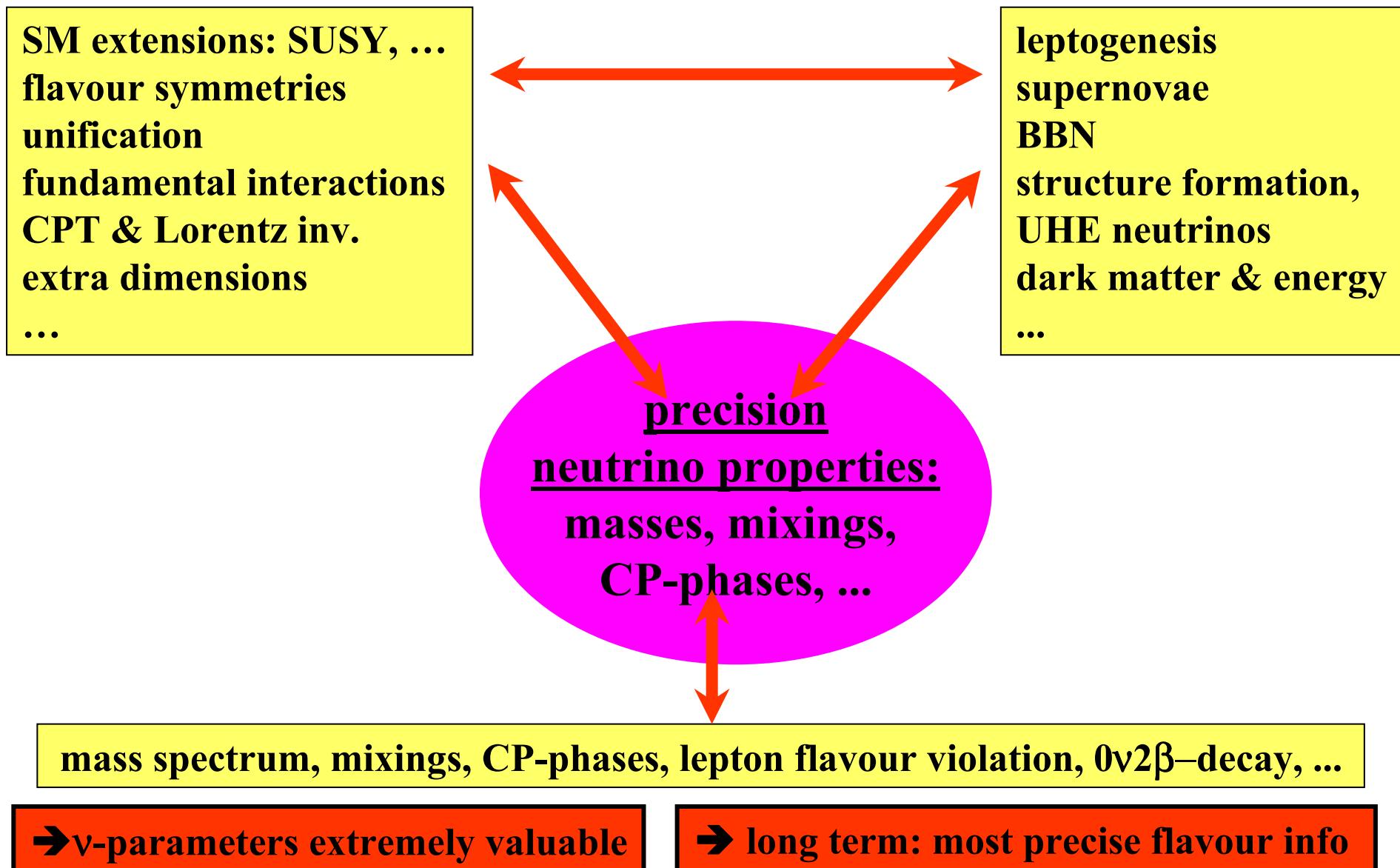


Baryon asymmetry with Dirac neutrinos, i.e. without L violation due to neutrinos

Other Topics (not covered)

- ν -cross sections
- NuTeV-anomaly
- GRBs
- AGNs
- horizontal air showers @ Auger
- τ -regeneration, OWL, ...
- theory:
 - detailed models of ν -masses & mixings
 - scenarios with $N_\nu > 3$ (sterile ν 's + small mixings)
 - limits on neutrino decay
 - bounds for non-standard interactions
 - connections to >SM & electro-weak symmetry breaking
 - GUTs, discrete flavour-symmetries
 - extra dimensions, strings, ...

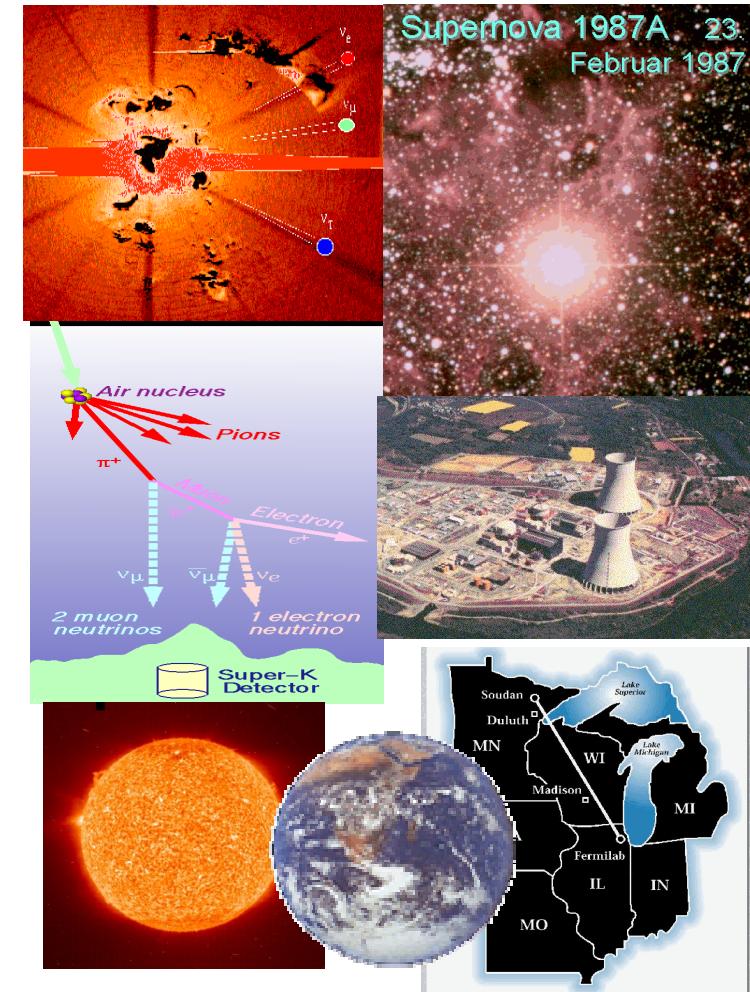
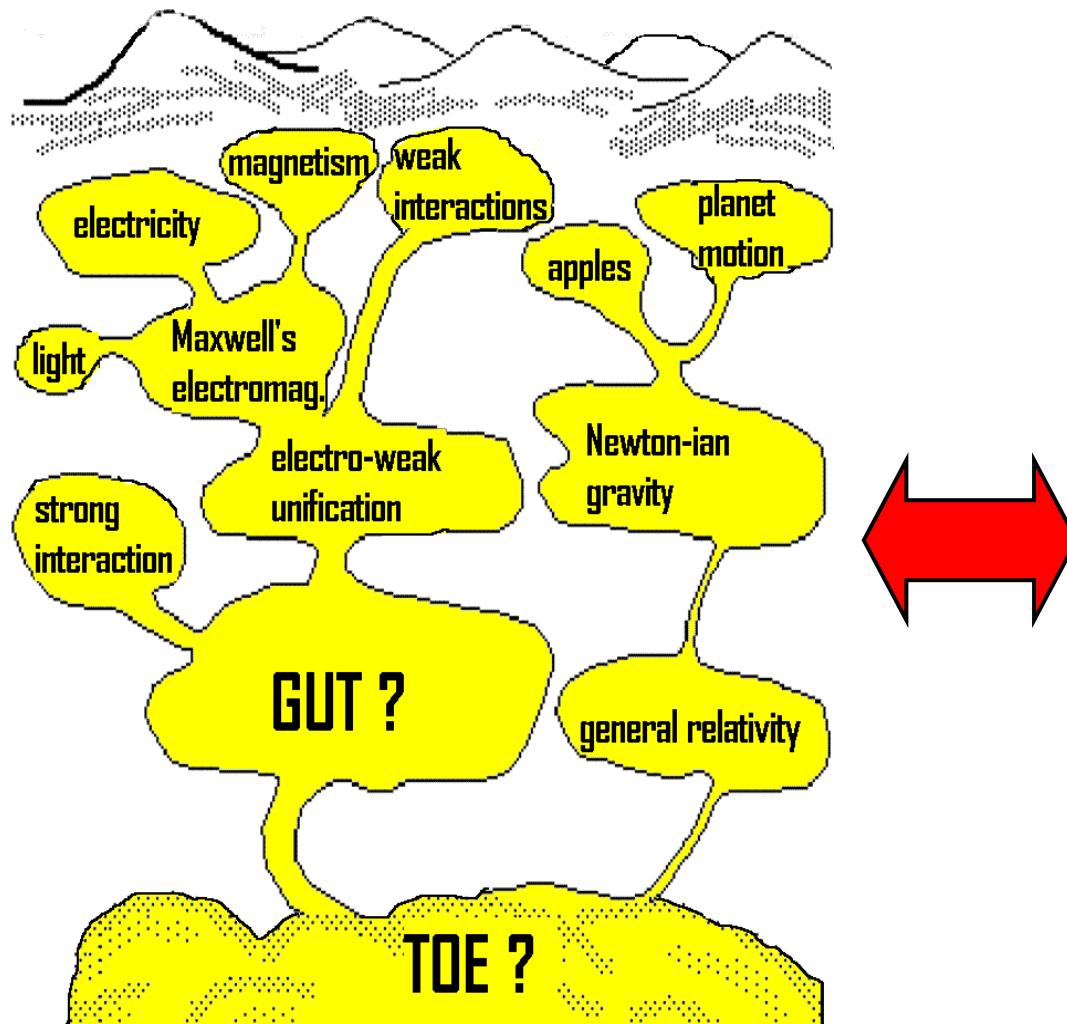
The Interplay of Topics



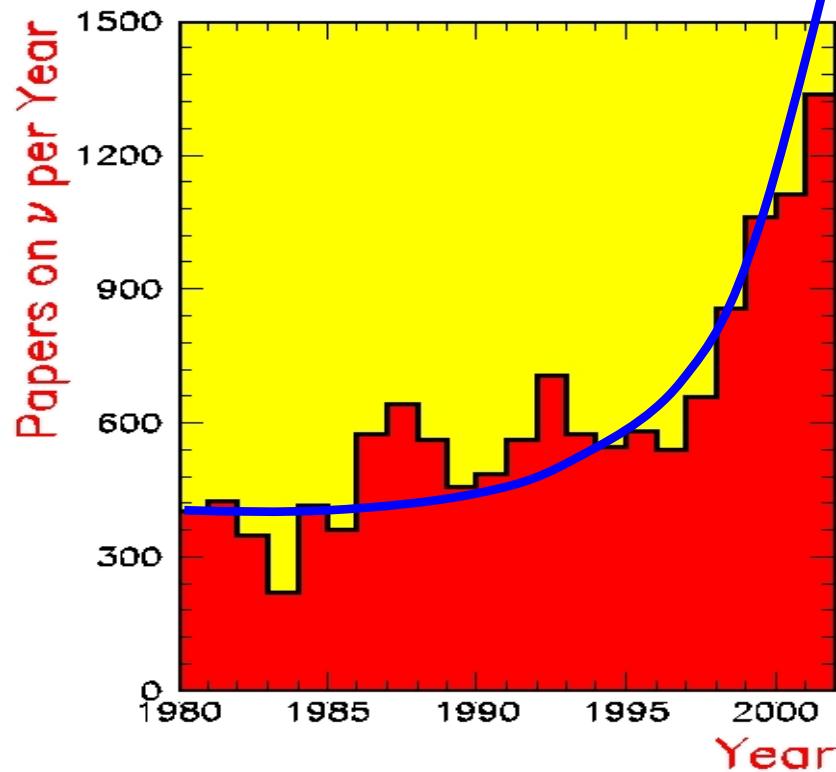
7. Conclusions

Conclusions

Neutrinos probe new physics in many ways!



Outlook:



$\sim e^{kt}$?

**ν -physics will
stay interesting!**